Final Report

1. ADMINISTRATIVE

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2. PUBLIC SUMMARY

We provide the projected fine-resolution future climate changes over Guam and American Samoa by the late 21st century (2080-2099) with both a high emissions scenario (RCP8.5) and a medium emission scenario (RCP4.5). We show that the surface air temperature (SAT) over Guam is likely to increase by 1.5 – 2.0 °C for RCP4.5 and by 3.0 – 3.5 °C for RCP8.5, while the projected SAT increases over American Samoa are slightly smaller. The projected annual mean future rainfall changes for Guam are not statistically significant in any location in either the RCP4.5 or RCP8.5 scenarios. However, American Samoa is projected to be wetter with the late 21st century mean rainfall increasing by ~20-25% at most locations. The frequency of weak tropical cyclones (TCs) will significantly decrease within 500 km around Guam, while that of strong TCs will increase. Similar trend is projected for American Samoa for RCP4.5, but both weak and strong TCs are likely to decrease significantly for RCP8.5.

3. TECHNICAL SUMMARY

A very high resolution regional atmospheric model was used to dynamically downscale the results of Coupled Model Intercomparison Project 5 (CMIP5) global coupled models to project the anticipated 21st century changes in rainfall, surface air temperature, surface wind, and surface radiative fluxes over Guam and the island of Tutuila over American Samoa. One of the major tasks for this project is to study the present-day TC activity and project the future TC frequency and intensity changes for Guam and American Samoa. To accomplish this task, we developed a new version of the Tiedtke cumulus parameterization scheme in the 20-km horizontal resolution regional climate model to better simulate the TC climatology. Two future scenarios, e.g., RCP4.5 and RCP8.5 (hereafter, named two future runs RCP45 and RCP85, respectively), are used to study the TC activity over the western North Pacific (WP, 110°E - 140°W, 0° - 39.5°N) and the South Pacific (SP, 145°E -140°W, 0° - 39.5°S). This is a new effort to study the TC activities with two different Representative Concentration Pathways (RCP) scenarios under the same model framework for two TC basins. Another task of this project is to downscale and project the atmospheric elements such as the surface air temperature (SAT), surface wind speed, and surface radiative fluxes. To achieve this goal, we further downscaled the 20-km model results to 4-km and then 0.8-km horizontal grids in order to better resolve the local complex topographic forcing. Hence, we provide extra-high resolution gridded present-day climate simulation and projected future climate changes for Guam and American Samoa with a state-of-art full physics regional climate model. To our knowledge, 0.8 km is the highest horizontal model resolution that has ever been employed to study regional climate changes by the research and applications communities.

4. PURPOSE AND OBJECTIVES

This project aims at to provide fine resolution climate information for Guam and American Samoa with the dynamical downscaling approach using a high-resolution regional climate model. There are two major objectives of this project: (1) to dynamically downscale the future precipitation and tropical cyclone (TC) frequency/intensity changes; (2) to dynamically downscale other geophysical driver, such as SAT, surface winds, surface radiative fluxes, etc. We have achieved these two major objectives. The downscaled climate data are important inputs for other research/applications groups in different disciplines, such as the freshwater resources, ecological, and biological modeling communities.

5. ORGANIZATION AND APPROACH

Following steps are conducted in order to downscale the climate changes for Guam and American Samoa.

(1) The setup of the regional climate model. We configured the Weather Research and Forecast model (WRF) with triply-nested meshes (Fig. 1). The outermost domain is large enough to cover almost the whole tropical and subtropical areas from the central Pacific to the western Pacific. The intermediate domain has 4-km horizontal resolution, and the innermost domain has a horizontal resolution of 0.8 km. The WRF model is widely used as a regional climate model to downscale region climates in different regions in the world. However, the realistic simulation of the TCs by WRF is particularly challenging and very sensitive to the cumulus parameterization scheme used. We developed a new Tiedtke scheme to better simulate the TCs, especially TC genesis frequency at the 20-km resolution. The flow chart for the experimental design is shown in Fig. 2. The driving fields for the atmosphere are the NASA Modern-Era Retrospective Analysis for Research and Applications (MERRA, Rienecker et al. 2011) reanalysis, and the sea surface temperature (SST) is from NOAA. Variables in the driving fields include temperature, wind, geopotential height, water vapor, etc. (Fig. 2a). For the future runs, the global warming signals are added to the present-day driving fields. This method is called the Pseudo-Global-Warming method (Fig. 2b), which is currently used in various applications and its advantages are briefly described below.

(2) Pseudo-Global-Warming (PGW) method. We adopted the PGW approach rather than a more straightforward dynamical downscaling applied directly to present day and future scenario integrations with an individual global model. State-of-the-art global coupled models when run freely generally display large biases in the simulated mean SST (with magnitudes as large as ~2K or more in many locations, e.g., Ashfaq et al. 2011) and other variables (e.g., Lauer and Hamilton 2013). Such biases may matter significantly for future projections (Sato et al. 2007; Ashfaq et al. 2011). By using the observed SSTs and lateral boundary conditions the PGW approach allows one to avoid potentially serious errors in reproducing the observed present day climate (Kimura and Kitoh 2007). The other major advantage of the PGW approach is that it allows the large-scale forcing of the model to be based on a multimodel ensemble mean of Global Warming Increments (GWIs). Lauer et al. (2013) conducted downscaling experiments with the outermost mesh of the Hawaiian Regional Climate Model (HRCM) using GWIs from 10 individual global models and compared the results with those from experiment using the multimodel mean GWI. Lauer et al. (2013) showed that despite a fairly large inter-model spread in the simulated climate changes, a single downscaling experiment using a multimodel mean GWI gives quite similar results to the ensemble mean of downscaling experiments using warming increments from each of the individual global models.

(3) The choice of the GWIs. The GWIs are a function of location, altitude and calendar date and were computed as the averaged global model simulated 2080-2099 results minus the 1990-2009 results. The monthly mean GWIs were interpolated linearly in time before being added to the 6-hourly reanalysis data used to create the lateral boundary conditions or daily SST data to create ocean surface boundary conditions for the HRCM. We used results from 12 CMIP5 models that provided all data needed for specifying the climate change contribution to the boundary conditions in HRCM. The selection of these 12 models was based on the availability of the atmospheric components (e.g., 3D temperature, geopotential height, wind, specific humidity, 2-m temperature, 2-m specific humidity and 10-m wind speed). We chose one model from each available research center to ensure the inter-model variability.

6. PROJECT RESULTS

(1) Tropical Cyclones (TCs)

a. Annual mean genesis frequency and frequency of occurrence,

The TC genesis was defined by the time when the 10-m wind speed reaches 17 m s^{-1}. The TC genesis locations were counted in each 5°×5° grid box. The TC genesis frequency in each grid box was the 20-year mean of TC genesis numbers in the box. Figure 3a shows the observed annual mean genesis frequency (shading) and the simulated genesis frequency in the present-day (PD) run (contour). The simulated PD genesis frequency distribution over the WP is similar to the observed. The maximum annual mean TC genesis number is around 0.8 in the PD simulation, which agrees well with that in observations, but the center of the maximum annual mean TC genesis frequency is located between 140°E and 150°E, which is about 15 degrees east of the observed center. Despite the TC genesis locations are similar in the PD simulation and the observation over the SP, the PD simulation obviously over-estimated the TC genesis number. In the future runs (Figs. 3b, c), it is clearly seen that the projected TC genesis frequency decreases west of 165°E and increases east of 165°E over the WP. The TC genesis frequency widely decreases over the SP in both warming scenarios. The vertical lines in Fig. 3b are the average TC genesis longitude for the PD (black), RCP4.5 (green) and RCP8.5 (red) runs. The TC genesis locations shift eastward over the WP and shift westward over the SP. The green dots in Fig. 3 indicate the future change that is statistically significant at the 90% confidence level. The change is more significant for the RCP8.5 scenario than for the RCP4.5 scenario.

In each 5°×5° grid box, we count the frequency of TC occurrence at every 6 hr. Figure 3d shows the 20-year mean TC occurrence frequency. The TC occurrence frequency in the PD run (contour) is very similar to that in observations (shading) in terms of the distribution and magnitude over the WP. The location of the maximum value of TC occurrence frequency from the PD run is about 5 degree south of that from observations (Fig. 3d). There are slightly more TCs east of 180° in the PD run (Fig. 3d). In spite of the distribution of TC occurrence frequency being well simulated in the PD run over the SP, the simulated PD occurrence frequency is much higher than the observed (Fig. 3d). Too many TCs and too long-lived TCs (not shown) in the PD run account for the large positive bias of TC occurrence frequency over the SP. Similar to the TC genesis frequency, the projected TC occurrence frequency is higher east of 165°E and lower west of 165°E over the WP for both the RCP4.5 and RCP8.5 scenarios (Figs. 3e, f), which is more significant in the RCP8.5 run. Different from the WP, the projected TC occurrence frequency almost homogeneously decreases over the SP (Figs. 3e, f). Note that the occurrence frequency increases in both RCP4.5 and RCP4.5 scenarios near the Hawaiian Islands, suggesting that the region could experience effect of more TCs in the future warmer climate.

b. TC intensity

Similar to the results from other studies using limited area models, the simulated TC intensity at around 20-km resolution is not as strong as the observed (e.g. Knutson et al. 2007; Walsh 2015). The strongest TC in our simulations has the maximum wind speed of 52 m s^{-1}. Figure 4 shows the annual mean TC frequency vs. maximum surface wind speed based on the 6-hr interval data for the WP (a) and the SP (b). Compared with the observations, the simulated TCs from the PD run have more frequent wind speed lower than 37.5 m s^{-1}, but less frequent wind speed higher than 37.5 m s^{-1} for both the WP and the SP (Figs. 4a, b). There are less frequent wind speeds lower than 42.5 m s^{-1}, but more frequent wind speeds higher than 42.5 m s^{-1} for both RCP4.5 and RCP8.5 runs over the WP. The frequency of TCs at all intensity bins significantly decreases mainly due to the significant reduction of TC genesis number in the future runs (RCP4.5 and RCP8.5) over the SP. The change is statistically significant especially for RCP8.5 at most of wind speeds. The future change is consistent with the findings by Knutson et al. (2015, see their Fig. 6a) in spite that their results are for all TC basins. The basic conclusion of fewer weak TCs but more strong TCs over the WP in the warmer climate is consistent with the earlier study of Murakami et al. (2012). They found that the frequency of weak TCs decreases, but the frequency of strong TCs slightly increases under global warming (Murakami et al. 2012; see their Fig. 8) over the Northern Hemisphere. The projected changes of the frequency of weak and strong TCs over the 500 km around Guam are very similar to the projected changes over the WP. The projected change over 500 km around American Samoa is similar to the change over the SP.

For the lifetime maximum surface wind speed, there are more weak TCs and more strong TCs compared to the observations for both the WP and the SP in the PD run (Figs. 4c, d). In the future runs, there will be more strong TCs for both RCP4.5 and RCP8.5 scenarios over both the WP and the SP. In comparison with the RCP4.5 run, the RCP8.5 run has more strong TCs, indicating a tendency of more strong TCs with more warming over the WP. However, the SP doesn’t show this tendency due to the significant reduction of total TC number in the RCP8.5 scenario run.

(2) Future changes from the 0.8 km simulation

Figure 5 shows the terrain height and land use/cover in the innermost domains with 0.8 km horizontal resolution for Guam and American Samoa. The model 3D and single level data are saved hourly. The simulated present-day (PD) daily mean surface air temperature (SAT), surface air specific humidity (Q_2), and surface wind speed are compared against those from observations at Guam and Pago Pago international airports, respectively. Note that both daily variables are averaged based on the hourly observations or model outputs. The biases of daily mean SAT are very small, indicating the significant control of surrounding SST on local SAT (Fig. 6). The biases of daily mean Q_2 and surface wind speed are also in reasonable ranges for both locations (Fig. 6). However, there is systematic bias in the simulated rainfall. Too much light rain (0.1 – 1 mm/day) accounts for the total dry bias for both locations (Fig. 6). Despite of some biases, the model simulated the basic atmospheric variables reasonably well.

The simulated PD 20-year mean SAT in the urban areas is about 1°C higher than the neighboring areas over Guam (Fig. 7a). The future SAT changes over Guam are in the range of 1.6 – 1.9°C for RCP4.5 scenario and 3.1 – 3.5°C for RCP8.5 scenario. The SAT increases by around 0 – 0.4°C more over land than over the neighboring ocean (Figs. 7b, c). Similar projections can be found for American Samoa (Figs. 7e, f). All SAT changes are statistically significant at the 95%

confidence level by paired student t-test. The projected future rainfall changes for Guam are small and do not pass the significance test in most areas (Figs. 8a-c), while the projected future rainfall changes for American Samoa indicate future increase by up to 25% for RCP4.5 scenario and up to 20% for RCP8.5 scenario, both significant at the 95% confidence level for most areas (Figs.7d-f). The PD surface evapotranspiration simulated surface evapotranspiration of about 3.2 – 5 mm/day (46 – 72 inches/year) except in the urban areas (Figs. 9a, d). The projected future surface evapotranspiration over Guam will slightly change but with low confidence level while the surface evapotranspiration is projected to increase over American Samoa, significant at the high confidence level (Figs.9b, c, e and f).

7. ANALYSIS AND FINDINGS

(1) The frequency of TCs will decrease but the intensity will increase for Guam, while both frequency and intensity will decrease for American Samoa.

(2) The projected precipitation change for Guam is insignificant, while American Samoa will get wetter at all locations by the late 21st century. Similar trends are projected for surface evapotranspiration.

(3) The projected surface air temperature will increase by up to 0.4°C over these islands than over the surrounding ocean.

8. CONCLUSIONS AND RECOMMENDATIONS

We have projected the climate change by the late 21st century for Guam and American Samoa. The projected surface air temperature (SAT) over Guam is likely to increase by 1.5 – 2.0 °C for RCP4.5 and 3.0 – 3.5 °C for RCP8.5, while the projected SAT increases over American Samoa are slightly smaller. The projected future rainfall change for Guam is not significant, showing slightly wetter for RCP4.5 and slightly drier for RCP8.5. However, American Samoa is projected to get wetter with the mean rainfall increase by up to 25% by the late 21st century. The frequency of weak tropical cyclones (TCs) will significantly decrease within 500 km around Guam, while that of strong TCs will increase. Similar trend is projected for American Samoa for RCP4.5, but both weak and strong TCs are likely to significantly decrease for RCP8.5. We have high confidence in the projected future daily mean surface air temperature (SAT) changes for Guam and American Samoa as well as the daily maximum and minimum SATs. Although we have relatively low confidence in the projected future rainfall changes, the daily extreme rainfall events are likely to increase. A scaling approach based on the CMIP5 model warming increments can be used to quantify the uncertainties due to the inter-model variability.

9. MANAGEMENT APPLICATIONS AND PRODUCTS

We expect that the dynamically downscaled atmospheric and land surface data will be used by other research/application groups. As also mentioned above, although the projected changes are for the late 21st century, the time interpolation from now to the end of this century can be used to drive applications models to assess the impacts of climate change on hydrometeorological and ecological systems by other research groups.

10. OUTREACH

A paper entitled "Projected future changes of tropical cyclone activity over the western North and South Pacific in a 20-km-mesh regional climate model." is under peer-review. Another paper entitled "Very-high-resolution dynamical downscaling of present-day and future climate for

Guam and American Samoa." is in preparation.

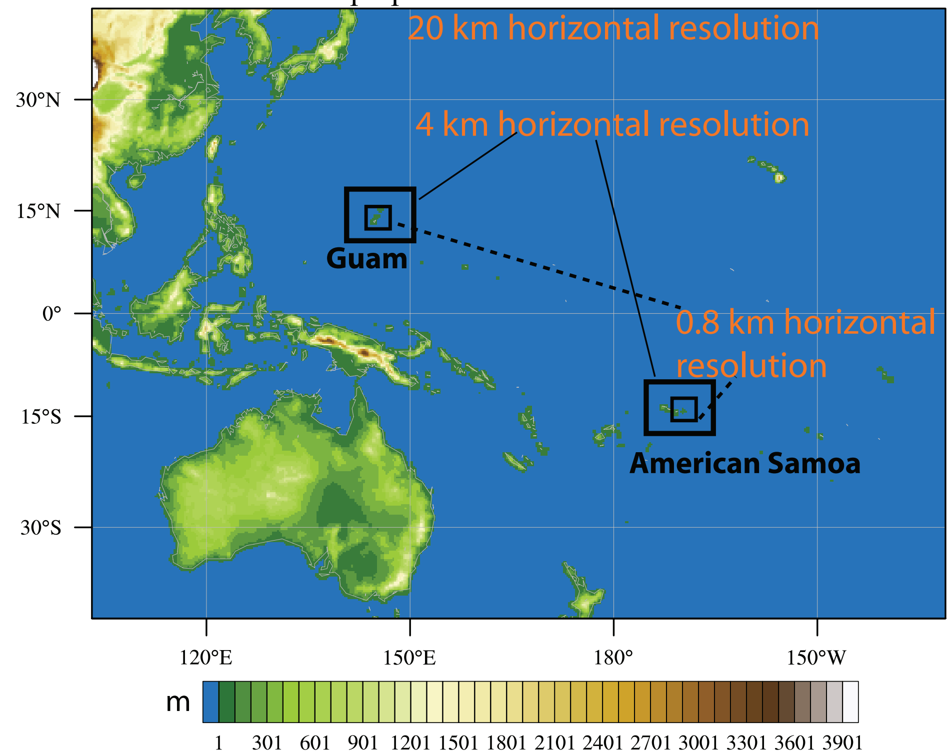

Figure 1. The configuration of the model domains for the simulations in this project.

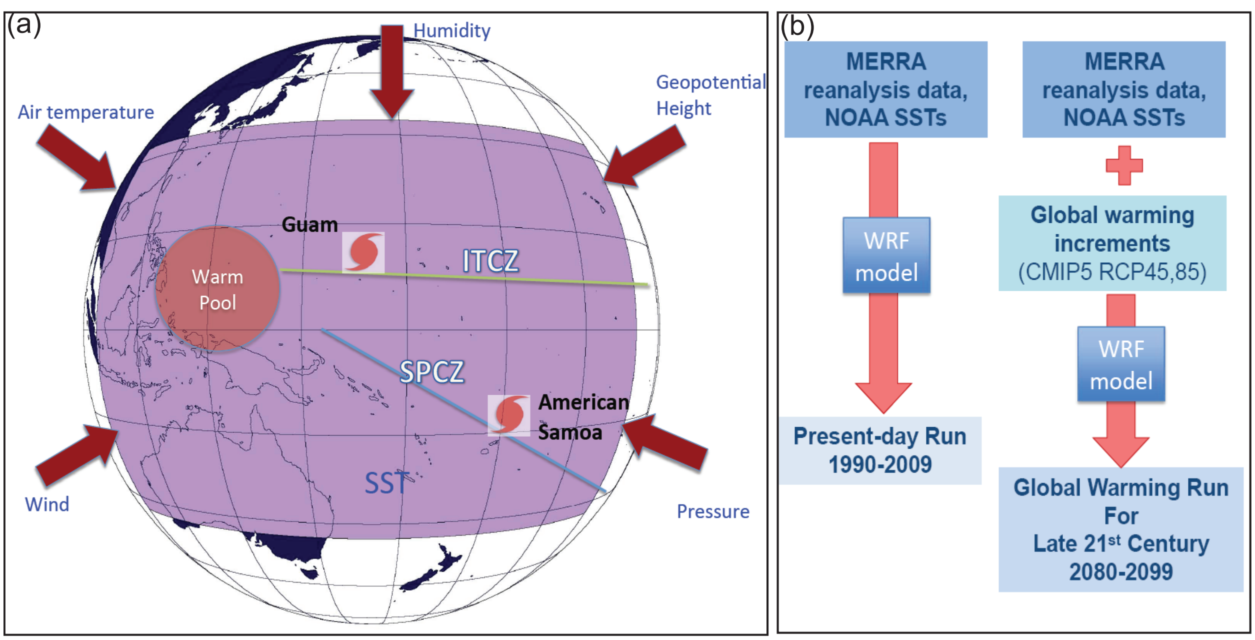

Figure 2. The CMIP5 multi-model mean warming increments are added to the lateral boundary (a). The flow chart for the dynamical downscaling is shown in (b).

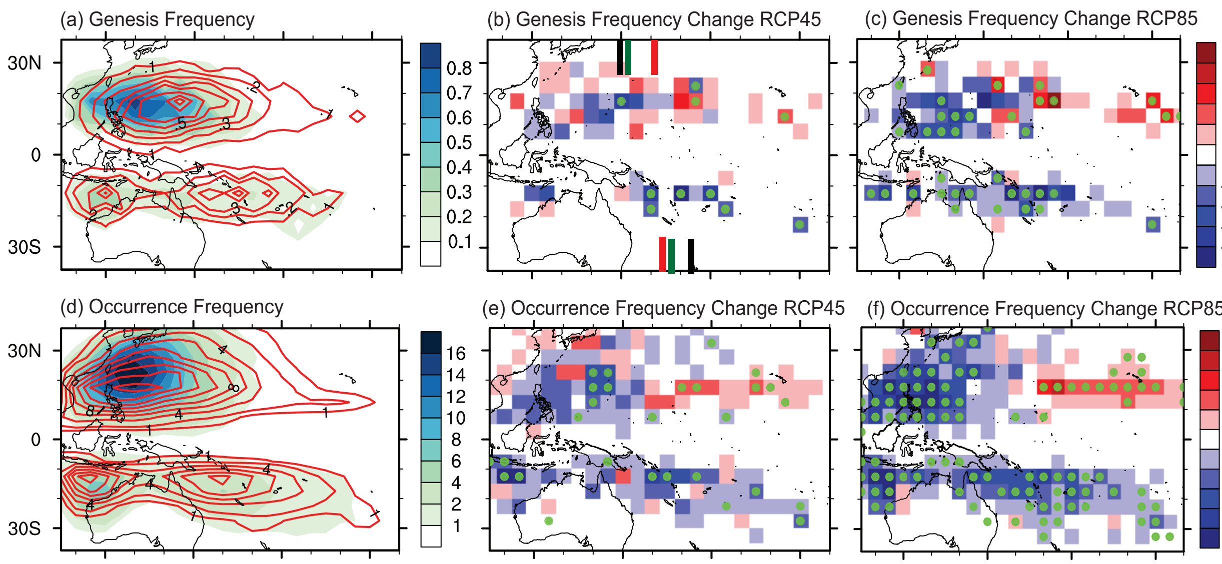

Figure 3. The annual mean TC genesis frequency (a) and occurrence frequency (d), during 1990-2009. The contour in (a) and (d) is for the PD simulation, while the shading is for observations. The contour has the same interval as the shading. The future change for annual TC genesis frequency (b, c) and occurrence frequency (e, f) are also shown. The TC genesis locations were counted every 5×5° grid box. The TC locations were counted every 5×5° grid box with 6 hour interval. The green dots in (b, c, e, f and h) indicate that the future change is statistically significant at the 90% confidence level. The vertical lines in (b) represent the averaged TC genesis longitudes for PD (black), RCP4.5 (green) and RCP8.5 (red).

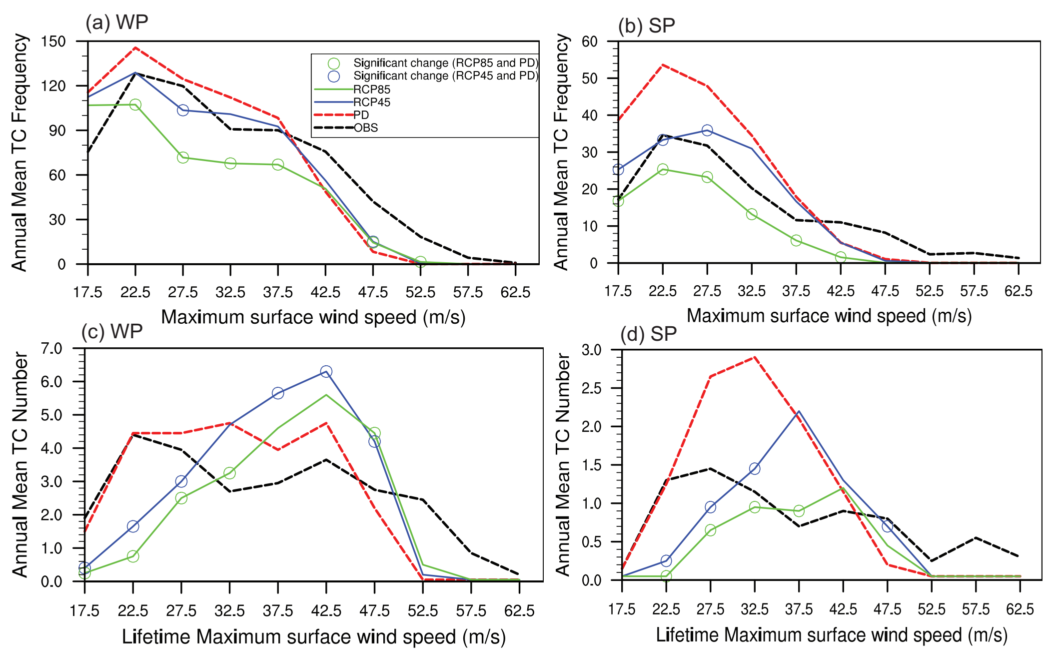

Figure 4. The annual mean TC occurrence frequency for maximum surface wind speed over the WP (a) and the SP (b), and the annual mean TC number for the lifetime maximum surface wind speed over the WP (c) and the SP (d). The circles indicate that the future change is statistically significant at the 90% confidence level.

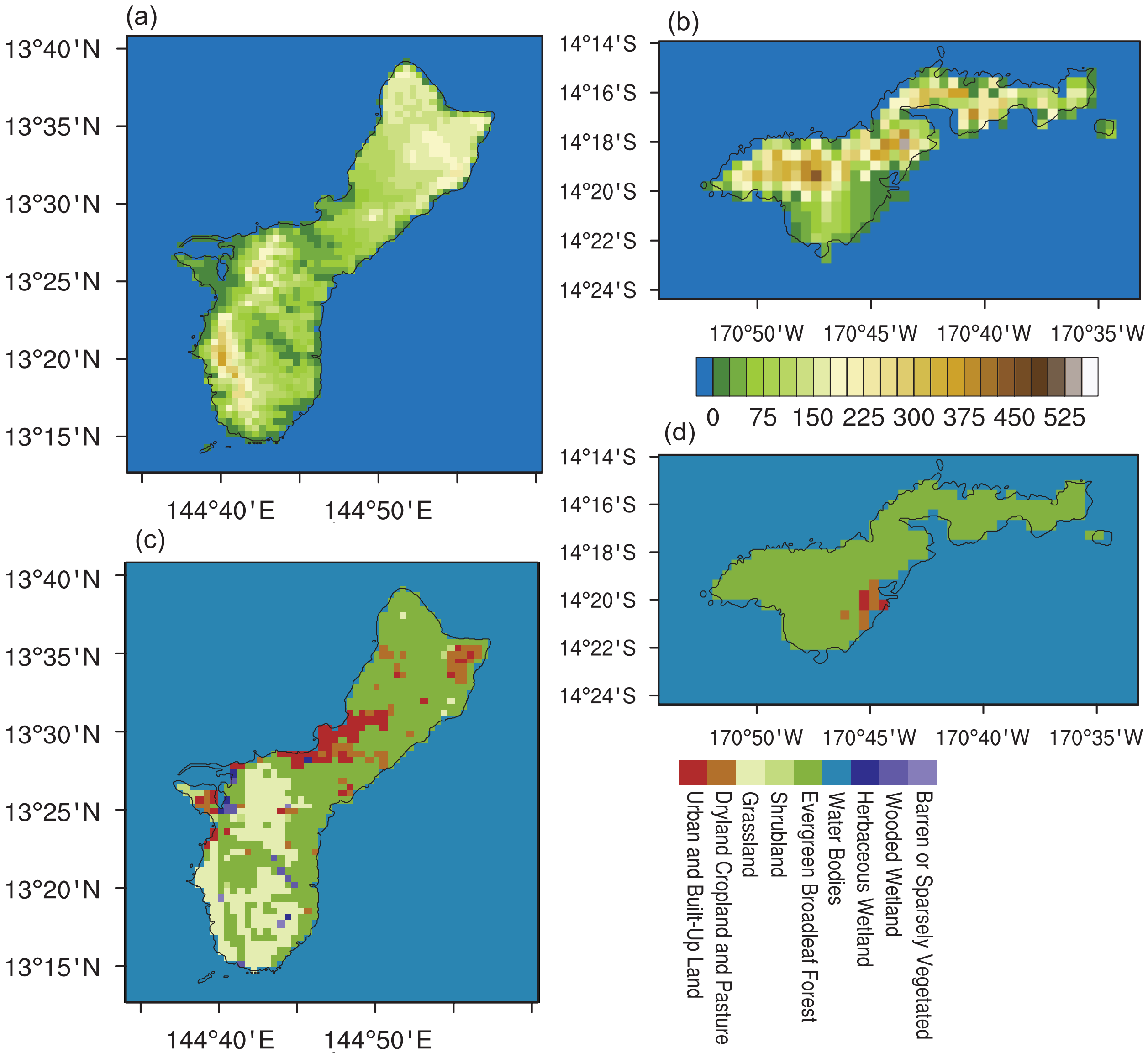

Figure 5. The terrain height (meters) of the inner domain (0.8 km) for Guam (a) and American Samoa (b) together with the land use/cover map for Guam (c) and Tutuila (d).

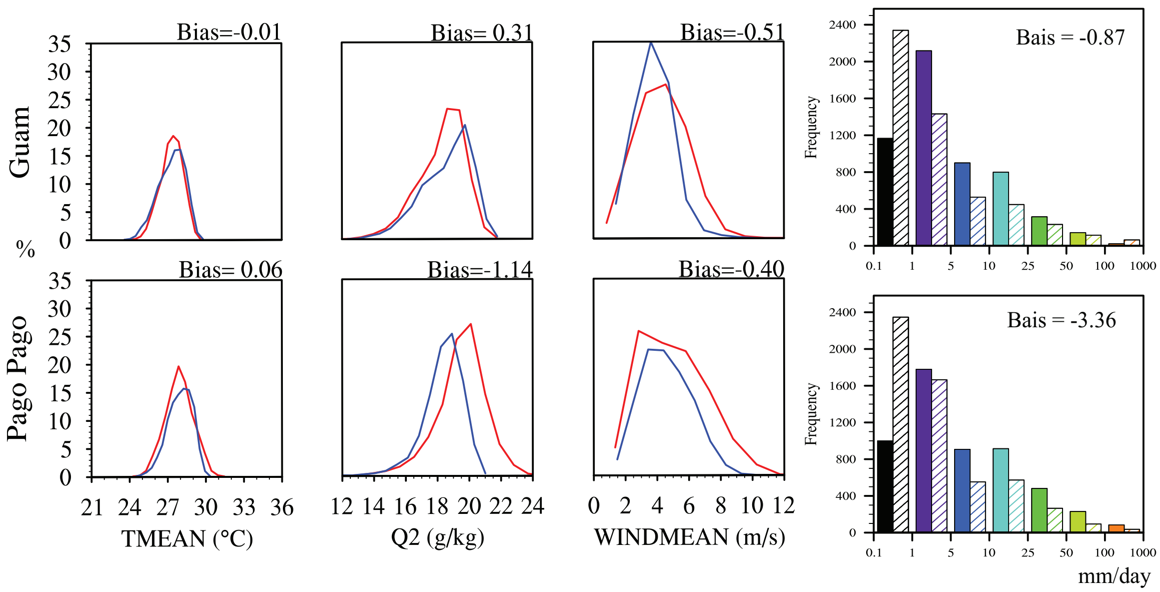

Figure 6. The simulated (blue line or hatched) and observed (red line or shading) frequency for daily mean surface air temperature (TMEAN), specific humidity (Q_2), wind speed (WINDMEAN) and precipitation for Guam international airport and Pago Pago international airport, respectively.

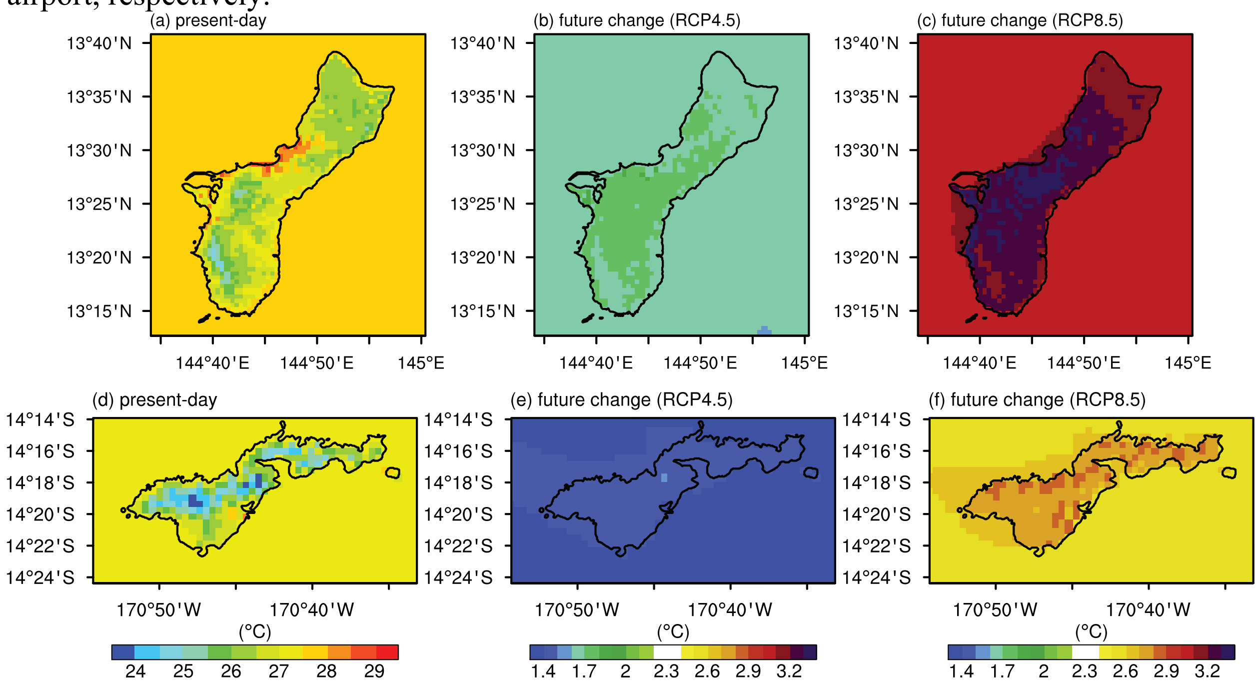

Figure 7. The simulated SAT for present-day (a, d), the future change for RCP45 (b, e) and the future change for RCP85 (c, f), respectively. All grids for the future changes are statistically significant at 95% confidence level.

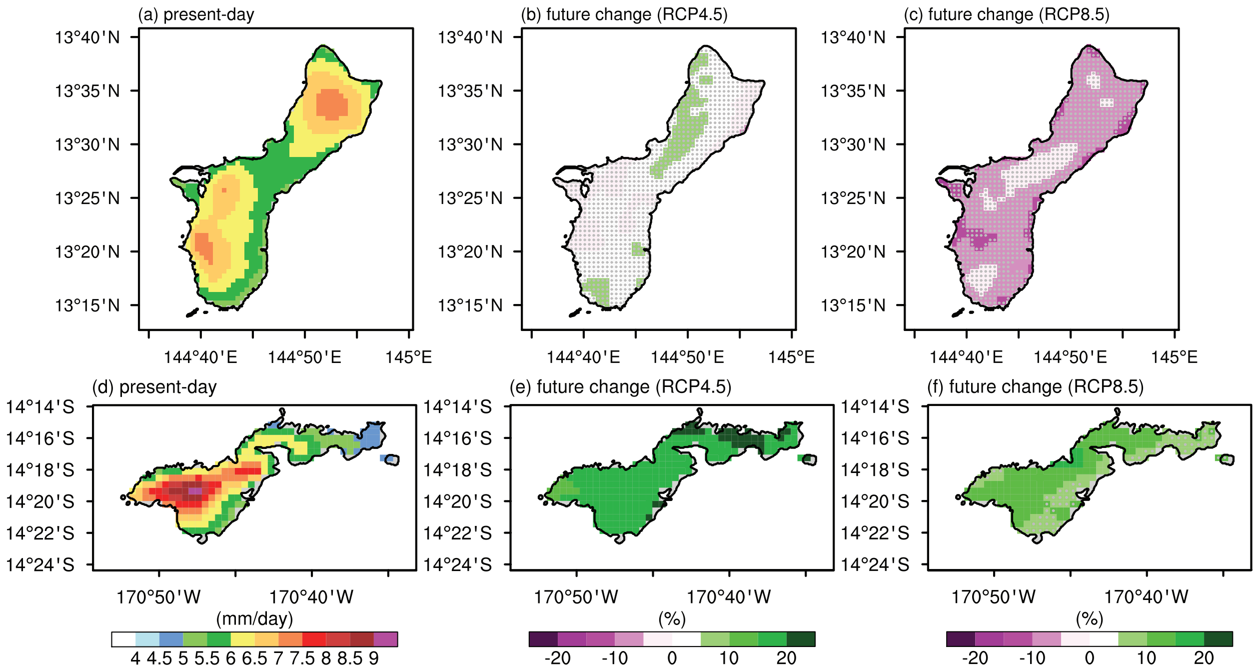

Figure 8. Same as Fig. 7 but for precipitation. The grey dots indicate the future changes are not statistically significant at the 95% confidence level.

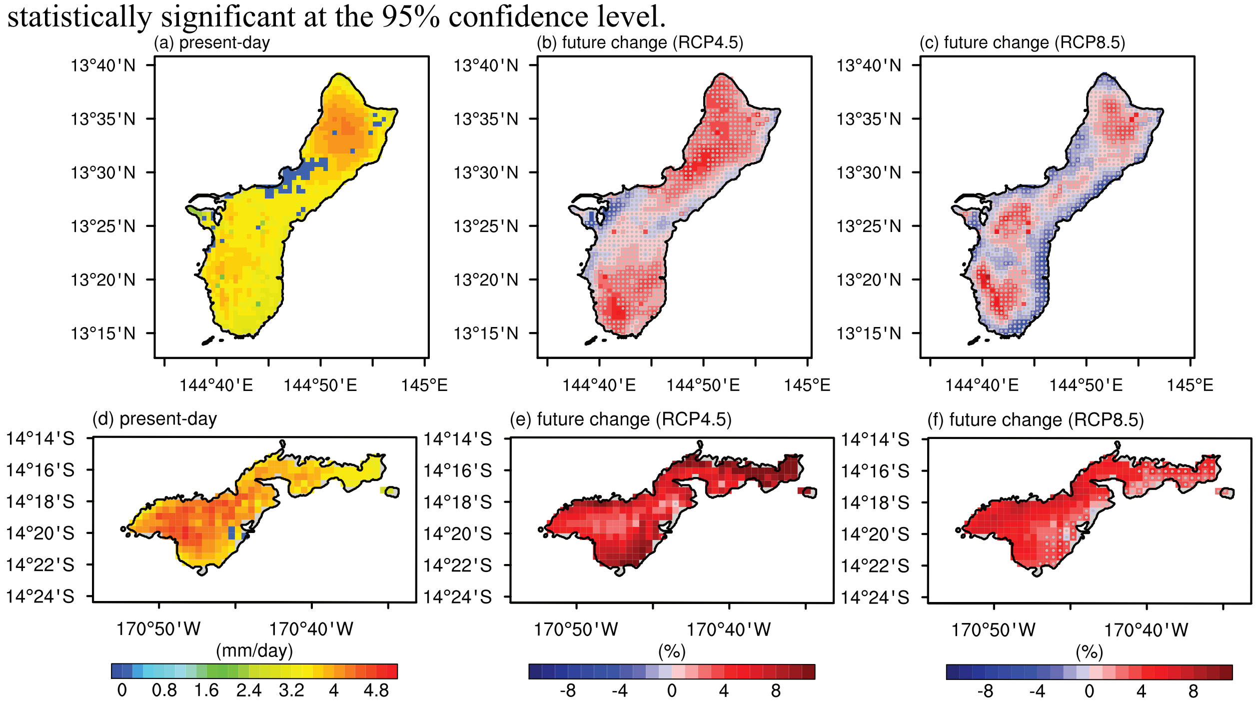

Figure 9. Same as Fig. 7 but for the evapotranspiration. The grey dots indicate the future changes are not statistically significant at the 95% confidence level.

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